1. Introduction

High-capacity (or high-data-rate) communications is required for human exploration of Mars and would allow science missions to execute and efficiently complete more data-intensive missions (refs. 1–1 and 1–2). Presently, science missions at Mars operate at very low data rates, such as 120 kbps (kilobits per second) for reporting telemetry from robotic experiments. Not only is this data rate insufficient to meet the expectations of future science missions that are striving to provide the same quality and quantity of return that is achieved on Earth-observing spacecraft, but it also falls short of expectations for activities associated with human exploration.

High-capacity communications over large planetary distances, however, is challenging. This occurs since signal strength, whether optical or radiofrequency (RF), decreases in inverse proportion to the square of the distance, so that getting enough power back to Earth from astronomical unit (AU) distances approaches new technological boundaries. The thesis of this work is that significantly higher capacity communication at RF is possible by utilizing new technology, which will allow increasing the spacecraft effective isotropic radiated power (EIRP) for relatively small increases in spacecraft mass and with reasonable increases in the Earth station effective aperture capabilities. By focusing specifically on the communications return link from Mars to Earth, the challenges and the spacecraft RF technologies that will provide the solutions are presented in the context of a critical piece of NASA's vision for exploration.

This report will demonstrate that Mars-to-Earth RF communications may achieve data rates as large as 1 Gbps (gigabits per second) with operational systems no later than 2020 using technologies that are at mid-technology readiness level (TRL) 4 to 5 or higher today. These technologies can be developed to TRL 6 or higher by 2020 without excessive monetary expenditures. This is addressed in two segments, the first of which is a discussion of spacecraft telecommunications transmit subsystem designs for a range of data rates (1 Gbps, 500 Mbps, and 100 Mbps) for both a Mars telecom orbiter at maximum Earth-Mars distance and a Crew Exploration Vehicle (CEV) in transit to the Red Planet. Broad recommendations for a CEV communication system will be discussed in the context of investigating how the requirements for an in-transit CEV and those of the transmitting Mars orbiter can simultaneously be met with a prudent allocation of Earth resources. The second segment explores the strategic and high-payoff technology investments that will offer design solutions for RF communications to meet the orbiter and CEV scenarios.

1.1 Approach: Data Rate as Key Parameter

A communications system is designed based on the following five criteria: data rate, bit error rate (BER), end-to-end delay, link availability, and available bandwidth.[1] Data rate is the parameter on which this report primarily focuses. Available bandwidth is typically dictated to the designer. The other three, though important, can mostly be addressed in other ways, leaving data rate as the key parameter for an efficient exploration of the RF communications design trade space.

Available bandwidth is of concern in that it will constrain the choices of modulation and coding—and hence the required SNR—for sufficiently high data rates. (Chapter 4 contains some

[1]Other error measures such as frame or block error rates may be specified, but any such measure ultimately ties back to a BER through the intervening coding and modulation.

discussion of the impact of a Ka-band bandwidth constraint on the data rates that might be achieved as the Earth-Mars distance varies.) Bandwidth-efficient modulation (BEM) and dual polarization are investigated as methods of bits-per-Hertz maximization. However, it should be obvious that the wider the bandwidth the greater the data rate. In this study we assume a 500 MHz bandwidth at 37 GHz. The impact of dual polarizations is to double the bandwidth. If the bandwidth were doubled the data rates discussed could be doubled as well. The hardware is now available to operation over many GHz of bandwidth, allowing operations that encompass the 32- and 37-GHz bands with the same hardware. We mention this here because it is important, but we do not attempt to work the bandwidth topic in this document.

For completeness the other three criteria are briefly described: (1) The link availability is determined by the architecture selected and is based on orbital mechanics and, where applicable, planetary weather conditions. The acceptable availability will be specified by the mission designers. (2) The end-to-end delay is determined predominantly by the light travel time. From Mars to Earth the delay may be from 3 to 22 min depending on distance. (3) The BER is determined by modulation, coding, and the available bit signal-to-noise ratio (SNR) at the receiver. The analysis contained in this report includes sufficient received signal strength to permit low BER (see appendix 4A for referenced link budget used in this report), and the issue is not addressed in any further detail.

Therefore while BER, delay, and availability are important, they will not be discussed, at length, in this report. Instead this effort will focus on Mars-to-Earth data rates as large as 1 Gbps, with emphasis on data rates and their implications, as opposed to the other parameters associated with communication systems. Chapter 2 will describe in more detail the surface robotic and human exploration scenarios as well as the Crew Exploration Vehicle (CEV)-to-Mars transit scenario that provide the rationale for the data rate selection and ranges used in the remainder of the report. Chapter 3 introduces the technical assumptions for the link design as preparation for chapter 4, which delves into the RF design trade space parameters of spacecraft subsystem mass and power as well as features of the Earth receive system. The capabilities in the spacecraft and on Earth at a distance of 2.67 AU are investigated: three different data rates (1 Gbps and 500 and 100 Mbps) for the relay and 1 Mbps for the CEV. Fixing the required resources to achieve the desired data rates at 2.67 AU means that greater data rates can be achieved for the CEV in transit (tens of Mbps) and for the relay in its orbit (a few Gbps). Chapters 5 and 6 provide a technical review of the primary technologies that enable high-capacity communications: antenna and power systems. Finally, chapter 7 integrates the design and technology aspects to evaluate approaches for mass minimization and assessing the associated technical complexity. Chapter 8 provides a summary of the results and highlights the conclusions of the work.

1.2 Background and Challenges of Spacecraft RF Design

1.2.1 Mass and Power

Those participating in the space community are all too familiar with the dynamic between mass, power, and cost in the design of a spacecraft. The communications subsystem is no exception; not only must a fine balance between communications system mass and power be found, but the design of the subsystem must be taken in context with the complete spacecraft and the total mass and power budgets.

The two primary contributions to spacecraft mass and power from the communications subsystem are the RF power subsystem and the transmit antenna. The RF transmitter is

characterized by its rated power, efficiency, and bandwidth, while the antenna is characterized by its throwing power or EIRP (effective isotropic radiated power). The EIRP is directly proportional to the antenna area and efficiency. Chapters 5 and 6 address candidate technologies for spacecraft antennas and transmitters, respectively. The description of power generating systems is also included in chapter 6. Since the achievable data rate is proportional to the transmit EIRP, both a large spacecraft antenna and a high-power transmit amplifier will be required for the highest data rates. Therefore an optimal communications system design will include a large spacecraft antenna, high-power transmitters, and robust surface receive system.

Examples of the relationship between the communications subsystem and the full spacecraft are provided by recent Mars missions such as the Mars Reconnaissance Orbiter (MRO) and Mars Global Surveyor (MGS). MRO, launched in 2005, has a Ka-band transmitter, a 35-W Ka-band traveling-wave-tube amplifier (TWTA), and spacecraft antenna of 3 m that will provide 6 Mbps coded at Mars (min. range) by December 2007 into a single 34-m Deep Space Network (DSN) antenna at Goldstone.[2] Spacecraft designers have typically not allocated very much mass and power to the communications equipment. As shown in and, for example, in Mars Global Surveyor the communications payload is the next to smallest subsystem in mass.

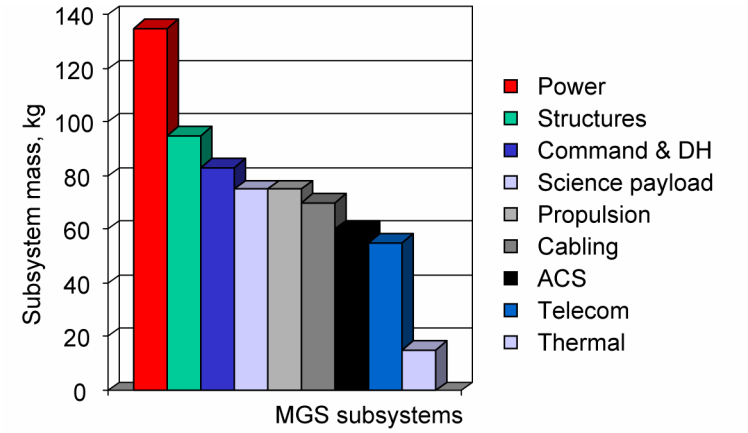

Figure 1–1.—Relative subsystem masses for Mars Global Surveyor.

TABLE 1–1.—ACTUAL VALUES ASSOCIATED WITH THE SUBSYSTEMS

Subsystem	Mars Global Surveyor subsystem mass, kg
Power	135
Structures	95
Command and DH	83
Science Payload	75
Propulsion	75
Cabling	70
ACS	60
Telecom—includes all communications	55
Thermal	15

[2]The other two sites will be at lower data rates due to elevation and weather issues, but this shows the possibility of much higher rates. For example if a 3.5-kW TWTA were used, the rate could be 100 times larger.

In comparing the data from various spacecraft, the communications subsystem package remains one of the smallest in mass. Therefore it becomes obvious that much larger data rates could be obtained if more mass were allocated to the communications systems. In this document, we are proposing to increase the telecom mass to about one and one-half or more of the mass for MGS (55 kg). This increase would allow for dramatic increases in data rates.

1.2.2 The Mars-Earth Dynamic

Some of the communications challenges result from the orbital geometry between Mars and the Earth. The variable distance has significant impact on the achievable data rate, the geometry imposes pointing requirements on the spacecraft, and the combination of geometry and thermal environment impacts the design of the antenna.

The light travel time from Mars to Earth varies by a factor of 7 depending on the distance between the two planets. That distance may be as small as 0.38 AU or as large as 2.67 AU over the next 25 years. The mean distance is 1.70 AU. Figure 1–3 shows the Mars-Earth distance over 30-year period and figure 1–4 shows the Sun-Mars-Earth angle over the same 30-year period. The large variation in distance has significant impact on the data rate available from the spacecraft, as discussed in a later chapter. A Mars-orbiting satellite for relaying communications from the planet would need sizable, but reasonable, communication assets to deliver power to the surface of the Earth sufficient to enable a data rate of 1 Gbps at maximum range.

The Mars relay satellite will continually point its antenna towards Earth during each revolution around Mars. Over a period of a Martian year, the Earth will move around the Sun, presenting a ±45° angle on each side of the Sun as viewed from Mars. As the spacecraft orbits Mars, it will point in the same direction, that is, the spacecraft will have inertial pointing. Nevertheless, a mechanism to maintain pointing finer tolerances than that normally provided by spacecraft Attitude Determination and Control System (ADCS). To maintain a low antenna pointing loss the spacecraft must be pointed with small error. Large antennas exacerbate the problem; they have smaller beam divergence angles, therefore, pointing loss becomes more sensitive to pointing error as the diameter increases. Details of fine-pointing mechanisms are discussed in chapter 5.

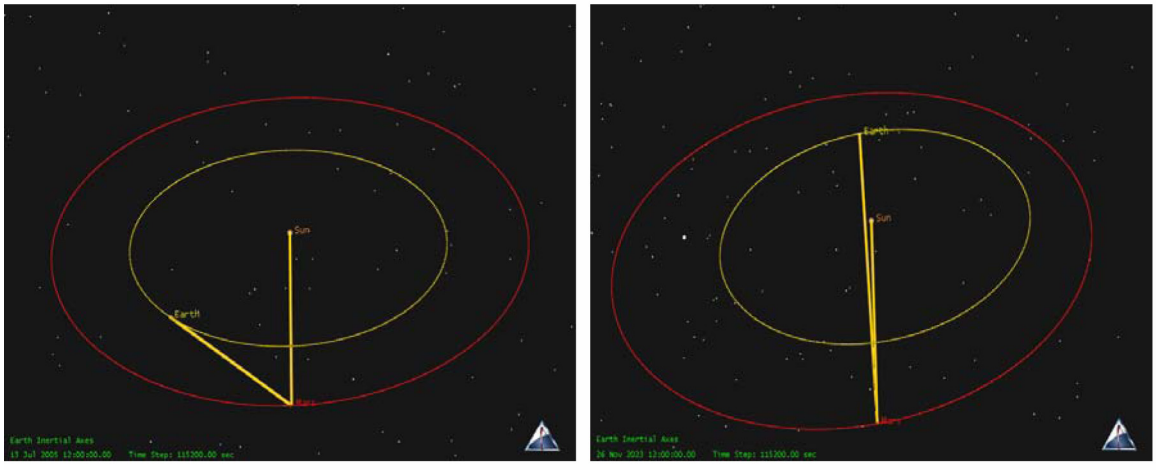

Figure 1–2.—Mars and Earth orbits.

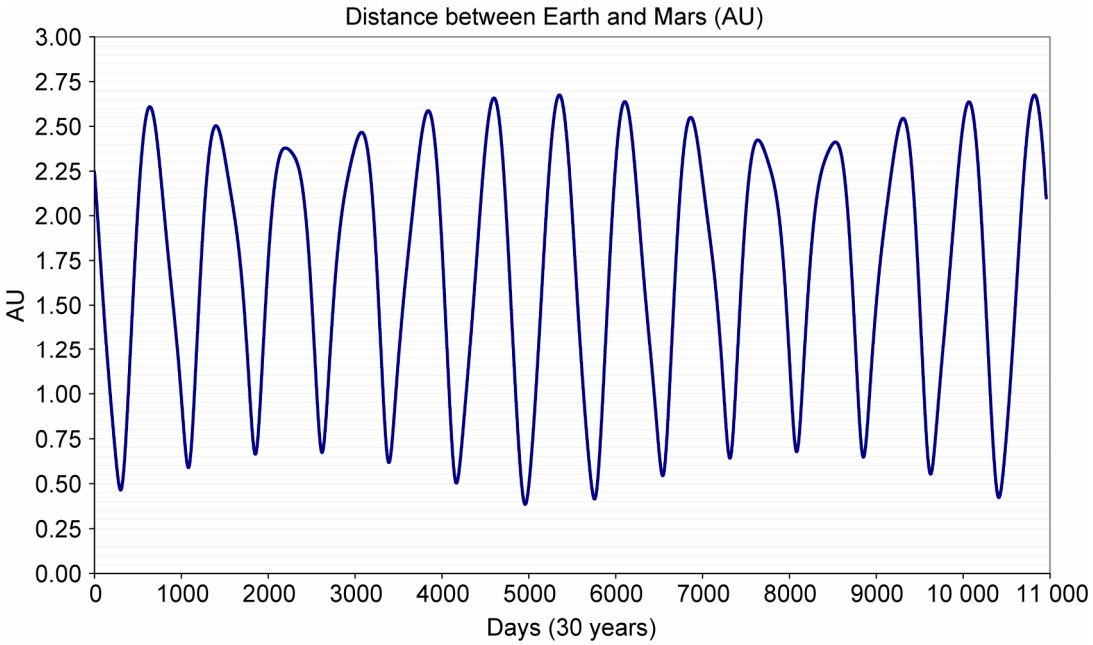

Figure 1–3.—Mars-Earth distance over 30-year period.

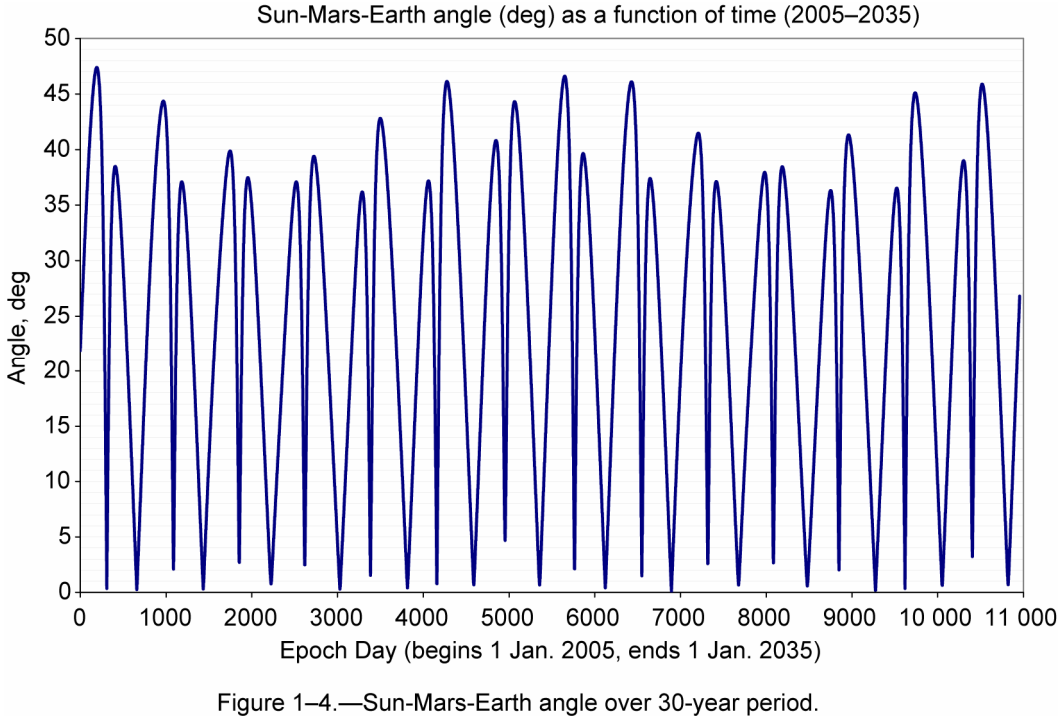

Figure 1–4.—Sun-Mars-Earth angle over 30-year period.

As the spacecraft's view of the Sun is occluded by Mars it cools off, and as the spacecraft returns into view of the Sun it begins to heat. Preliminary thermal calculations confirm that there is a small but non-negligible thermal variation. Not only will thermal variations cause distortion of the antenna, but the spacecraft may also need to be designed to minimize the relative thermal expansion of the spacecraft body, something that the commercial satellite industry has already addressed. Though a large antenna absorbs greater radiation, the material and structure of the antenna will impact its thermal behavior. For example, a mesh antenna (considered in ch. 5) would not absorb as much as a solid antenna.

1.2.3 The Earth Ground System

There are two major components to a communications system, the transmitter and the receiver. For high-capacity RF from Mars, choices for the first receive terminal location include the Earth's surface, a near-Earth orbit, or the lunar surface. An Earth-surface-emplaced terminal seems the clear choice, barring frequency selections for which there may be significant near-Earth interference. The most cost-effective receivers are large Earth-based antennas.

The DSN currently uses large Earth antennas, either 34 or 70 m, to capture sufficient power to make the RF communications possible. To cope with future communications at greater distance or higher rates, NASA is considering a plan to evolve to a network of 12-m antennas that can be arrayed to receive data from space by providing the required effective aperture on a case-by-case basis. Optical communications, a second option to address these needs, has yet to be demonstrated at these distances.

As the design trade space and technologies are explored in following chapters, the impacts of these challenges of mass and power balance, large and variable communications distance, pointing requirements, thermal stresses, and ground system characteristics will all be discussed in greater detail.

1.3 References

1–1 Vision for Space Exploration.
1–2 DSN 100 Year plan.